IJSPT

ORIGINAL RESEARCH

EFFECTS OF FOREFOOT RUNNING ON CHRONIC EXERTIONAL COMPARTMENT SYNDROME: A CASE SERIES

MAJ Angela R. Diebal, PT, DPT[1]
Dr. Robert Gregory, PhD[2]
COL Curtis Alitz, MD[3]
LTC J. Parry Gerber, PT, PhD[1,4]

ABSTRACT

Introduction: Chronic exertional compartment syndrome (CECS) is a condition that occurs almost exclusively with running whereby exercise increases intramuscular pressure compromising circulation, prohibiting muscular function, and causing pain in the lower leg. Currently, a lack of evidence exists for the effective conservative management of CECS. Altering running mechanics by adopting forefoot running as opposed to heel striking may assist in the treatment of CECS, specifically with anterior compartment symptoms.

Case Description: The purpose of this case series is to describe the outcomes for subjects with CECS through a systematic conservative treatment model focused on forefoot running. Subject one was a 21 y/o female with a 4 year history of CECS and subject two was a 21 y/o male, 7 months status-post two-compartment right leg fasciotomy with a return of symptoms and a new onset of symptoms on the contralateral side.

Outcome: Both subjects modified their running technique over a period of six weeks. Kinematic and kinetic analysis revealed increased step rate while step length, impulse, and peak vertical ground reaction forces decreased. In addition, leg intracompartmental pressures decreased from pre-training to post-training. Within 6 weeks of intervention subjects increased their running distance and speed absent of symptoms of CECS. Follow-up questionnaires were completed by the subjects at 7 months following intervention; subject one reported running distances up to 12.87 km pain-free and subject two reported running 6.44 km pain-free consistently 3 times a week.

Discussion: This case series describes a potentially beneficial conservative management approach to CECS in the form of forefoot running instruction. Further research in this area is warranted to further explore the benefits of adopting a forefoot running technique for CECS as well as other musculoskeletal overuse complaints.

Key Words: anterior compartment syndrome, fasciotomy, forefoot running, shin splints.

[1] Keller Army Community Hospital, West Point, NY, USA
[2] Assistant Professor, Biomechanics, United States Military Academy, West Point, NY, USA
[3] Orthopedic Surgeon, Keller Army Community Hospital, West Point, NY, USA
[4] Baylor University, Waco, TX, USA
IRB approval was granted for the study protocol by Keller Army Community Hospital on 5 OCT 2010
This research was conducted at the United States Military Academy, West Point, NY. At the time of the research, MAJ Diebal was completing a post professional sports medicine physical therapy residency under the mentorship of Dr. Gerber as well as completing her DScPT in Physical Therapy from Baylor University, Waco TX. The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the US Army, the Department of Defense, or the United States Government.

CORRESPONDING AUTHOR
MAJ Angela Diebal
Keller Army Community Hospital
West Point, NY 10996
Email: angie.diebal@us.army.mil

INTRODUCTION

Since the 1970's the popularity of aerobic exercise has increased tremendously.[1] Running has long been a primary popular choice of aerobic exercise for many people and boasts several positive health benefits. It can be performed virtually anywhere without any special equipment, can complement most physical training programs, and can improve aerobic endurance with three 30 minute training sessions per week.[2] As the number of individuals participating in leisurely jogging and running activities has increased, the incidence of injuries has also increased.[3,4]

In an effort to prevent, treat, and reduce running injuries, a current trend in rehabilitation has centered on modifying running technique. Several running techniques that have recently gained popularity are Chi Running, Barefoot Running, Evolution Running, and the Pose Method.[5-7] These running styles are similar in the sense that they aim to eliminate the initial heel strike at ground contact by promoting a forefoot strike upon impact. While much more research is needed to determine if adopting such a running style can help prevent injuries, several authors have demonstrated that a significant reduction of ground reaction forces can occur if the heel strike is eliminated at initial impact.[8-10] Research has not been thoroughly conducted to determine what musculoskeletal conditions would respond favorably or not so favorably to changing running styles. Theoretically, adopting a forefoot running style would be best suited for those conditions that could benefit from reduced ground reaction forces while running (i.e., stress reactions/fractures, anterior knee pain, back pain, etc.). This case series presents preliminary data which suggests that chronic exertional compartment syndrome (CECS) is one musculoskeletal condition that may respond positively to adopting an alternate running style.

CECS is defined as a condition that causes lower leg pain and disability during exercise in the presence of increased intramuscular pressure in a closed fibro-osseous space.[3,11,12] This condition is most prevalent in young adult athletes and occurs with increased frequency among members of the military.[11,13,14] The exact cause of CECS remains unclear but it is speculated that the pressure increase is due to arterial spasm, capillary obstruction, arteriovenous collapse, venous outflow obstruction, muscle hypertrophy, fascial inflexibility, or a release of protein bound ions.[4,11,12,15] The high pressure may cause vascular occlusion and decreased tissue perfusion which may lead to ischemic pain that often occurs bilaterally.[16-19] The anterior compartment is the most common location for CECS to occur, with runners accounting for 69% of all cases.[14,19] The anterior compartment is bordered by the tibia, fibula, interosseous membrane, and the anterior intermuscular septum. It consists of the tibialis anterior muscle and anterior tibial artery, extensor digitorum longus, extensor hallucis longus, fibularis tertius muscles, the anterior tibial artery, and the deep fibular nerve. Diagnosis of this condition is difficult due to the lack of clinical signs and symptoms. History and physical examination alone are often considered inadequate for the diagnosis of CECS.[20] Intracompartmental pressure measurements confirm the diagnosis of CECS and help differentiate it from other conditions causing exercise induced pain.[21] Pedowitz et al developed intramuscular pressure thresholds using a slit catheter to further assist in the diagnosis of CECS.[18] For those suffering from CECS, running activities present a significant problem. As the compartment pressure increases, a person may develop lower leg pain, sensory abnormalities, and muscle weakness which eventually results in a premature cessation of the activity.[4,11-13,20,22-27] Upon cessation of the activity the compartment pressure decreases, pain subsides, and the functional examination returns to "normal", typically within ten minutes.[11,12] Recommended non-surgical management for CECS includes anti-inflammatory drugs, stretching, prolonged rest, decreasing or avoiding the problematic activity, orthotics, and massage.[16,20,23,25] None of these conservative approaches have yielded consistently positive long term results; however, no randomized controlled studies exist in the literature to truly investigate conservative management techniques.[28] If those with CECS do not desire to modify their activity level, the only effective treatment for this condition is surgical management in the form of a fasciotomy.[16,25] While the majority of patients do well following surgery, approximately 3-17% of individuals undergoing fasciotomy experience less than favorable outcomes such as ankle pain, reoccurrence of symptoms, decreased sensation at the incision site, numbness at the lateral leg, hypersensitivity to touch, and paresthesias in the legs.[16,19,29,30]

One conservative management approach that has not been investigated, but theoretically could assist those with anterior CECS, is altering running technique. Kirby et al found that anterior compartment pressures were significantly influenced by running style, reporting anterior compartment pressures were increased when a heel striking gait pattern was utilized.[15] It has also been well documented that forefoot striking as opposed to heel striking causes a decrease in ground reaction forces, stride length, and ground contact time and an increase in step rate.[8-10,31-42] To the authors' knowledge, the modification of running technique as an intervention for CECS has not previously been investigated. Incorporating the use of a systematic instructional model, which focuses on landing on the forefoot as opposed to the heel, may assist in controlling the elevation of compartment pressures with running. If successful, this could allow those suffering from CECS the ability to run longer without symptoms and possibly reduce the need for fasciotomy.

The purpose of this case series is to describe the outcomes for two subjects with anterior CECS through the implementation of a systematic conservative treatment model focused on forefoot running.

CASE DESCRIPTION

Both participants were given a verbal explanation of the study protocol and provided written informed consent prior to testing. Approval was granted by the Institutional Review Board at Keller Army Community Hospital.

Case 1: A 21-year old female (154.9 cm, 52.6 kg) presented to physical therapy with a four year history of bilateral anterior and lateral lower leg pain that occurred while running. The patient reported leg symptoms while running that began predictably before 0.8 km resulting in pain and tightness, which progressively worsened to include numbness and pressure with pain throughout the exercise. She reported the ability to tolerate the leg pain for several kilometers if running on flat surfaces at a slower pace; however, she could tolerate less than 1 km if she ran up hills. She reported that upon cessation of running her symptoms would completely resolve within 5 to 10 minutes.

The initial physical examination at rest was unremarkable (i.e., full ankle and knee range of motion (ROM) and strength, no tenderness or compartment tightness to palpation, and full functional ability to squat and hop without symptoms). A running evaluation was conducted by real time observation using a commercial grade treadmill (LifeFitness, 97Ti, Franklin Park, IL). The patient ran at a self-selected pace of 11 km per hour, demonstrating a heel striking and over-striding gait pattern. The patient reported an onset of pain in the anterior and lateral aspect of both lower legs after running 3 minutes, at which time an audible and visual foot slap was observed for both lower extremities. After 0.8 km (5 minutes, 10 seconds), the patient reported a 6/10 pain on the left leg (2/10 on the right leg) and requested to end the session. A physical examination immediately following revealed an appreciable firmness and tenderness to palpation in both anterior compartments, and decreased dorsiflexion strength bilaterally (4+/5). Based on history and physical examination, a preliminary diagnosis of leg pain consistent with CECS was made.

The subject returned the following day for the collection of kinematic and kinetic running data. An instrumented treadmill was utilized (Kistler-Gaitway, Zurich, Switzerland) to assess variables illustrating running technique such as; step length, step rate, vertical ground reaction force (GRF), and impulse, (Table 1). Impulse is defined as the product of the

Table 1. *Kinematic and Kinetic Variables for Subject Number 1.*

Kinematic & Kinetic Measurements		
	Pre-intervention	**Post-intervention**
Step Length	1.15 m	1.05 m
Step Rate	2.74 steps/s	2.99 steps/s
Vertical GRF	1384.42 N (2.68 BW)	1286.34 N (2.44 BW)
Impulse	193.64 Ns	183.56 Ns

m= meters; s= seconds; GRF= ground reaction forces; N= newtons; BW= body weight; Ns= newton seconds

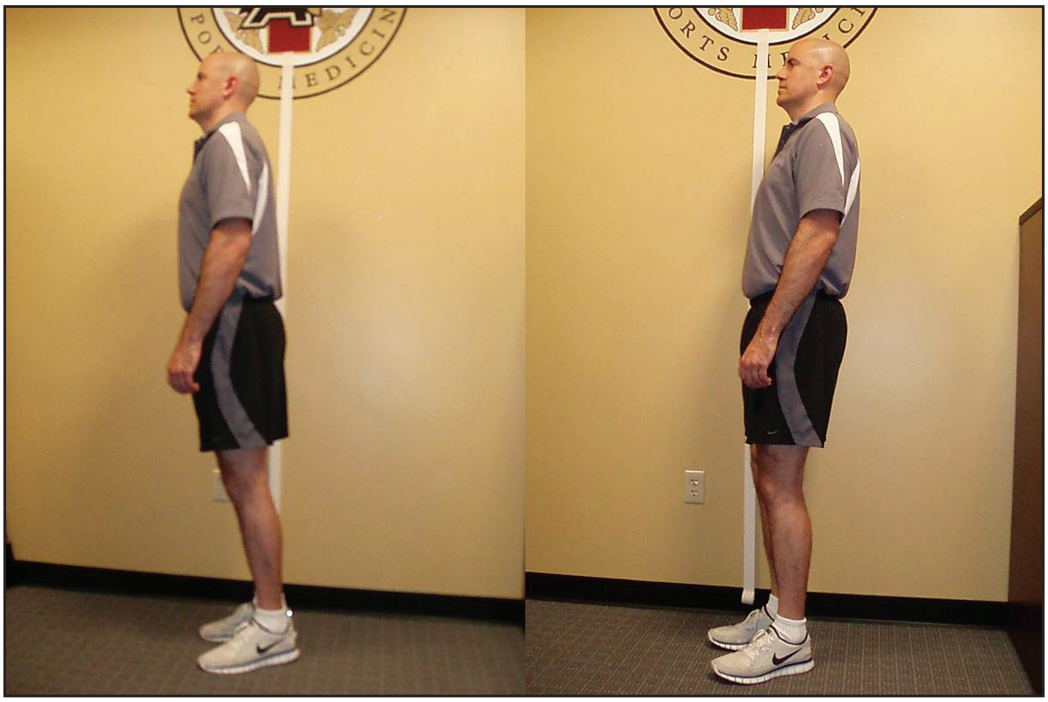

Figure 1. *Weight Shifting—In this drill the patient focuses on shifting the pressure from the heels onto the forefeet to improve perception of how minute adjustments can dramatically change body weight during support.*

magnitude of a force and its time of application. It is specifically the area under a vertical ground reaction force-time curve. In a third visit, pre- and post-exercise intracompartmental pressures of the anterior compartments were measured by an orthopedic surgeon (refer to Tables 6 and 7 for values) using a Stryker Intracompartmental Pressure Monitor (Side Port Needle, Kalamazoo, MI).[20,43,44] Positioning of the knee, leg, and foot was standardized for all measurements. Post-exercise pressure measurements were taken at 1 minute following exercise cessation. Due to the elevation in post exercise intercompartmental pressure, the diagnosis of CECS was made by the orthopedic surgeon.

Physical therapy intervention was initiated that focused on modifying the patient's running technique. The patient was instructed in a forefoot running technique on both land and treadmill, with the aim of eliminating the initial heel strike and consequently reducing ground reaction forces.[7,45] Training included increasing her running step rate to 3 steps per second and using her hamstrings to pull her foot from the ground versus push her foot from the ground using the gastocneumius.[9] A digital metronome (Seiko, DM50S, Singapore) was also utilized to increase step cadence to 180 steps per minute. Focused training drills and exercises consisted of weight shifting, falling forward, foot tapping, high hopping, and running with a specialized belt (EZ Run Belt, Posetech.com) as described by Romanov (Figures 1-5).[7,46] The subject also practiced running barefoot with verbal cueing to "run quietly" to eliminate the tendency to heel strike upon ground contact. Feedback was provided using video recorded from a

Figure 2. *Falling Forward—In this drill the patient focuses on falling forward while maintaining the funning pose in front of a wall. Start close to the wall and move farther from the wall as comfort level increases.*

Figure 3. *Foot Tapping—In this drill the patient pulls the foot from the ground using the hamstrings and allows the foot to fall back to the ground using gravity. The patient does not actively lower the foot.*

Figure 4. *High Hopping—Start in the running pose, and work on hopping, progressing to the point where the heels touch the buttocks. Attempt to maintain quadriceps relaxation throughout this drill.*

Figure 5. *The EZ Run Belt (Joe Sparks, Perrysburg, OH). This is a training tool to assist learning and self correction of running gait. It assists by pulling the foot from the ground and helps prevent over striding.*

commercial camera (Flip Video, Cisco, California) and placed on a personal laptop computer (MacBook Pro, Apple) to help demonstrate and correct running errors. This instruction was conducted 3 times a week for approximately 1 hour each and took place over the course of 6 weeks. The instruction initially consisted of the training drills listed in Figures 1-5 and then progressed to forefoot running intervals for distances of .25 km with a two minute walking period between intervals. Running endurance was gradually progressed as proper running form was maintained for longer distances between walking bouts. Instruction during the last 3 weeks of training mainly focused on improving running speed and endurance while maintaining proper form during running duration.

OUTCOMES

At 6 weeks post-intervention, the physical examination, including intracompartmental pressures, and the kinematic and kinetic treadmill measurements were repeated. The physical examination was unremarkable before and after running. The patient ran 5 km (26 minutes, 18 seconds) on the treadmill without any pain complaints; treadmill testing concluded at a predetermined distance of 5 km. The force plate treadmill measurements and the pre- and post-intracompartmental pressures of the anterior compartments are presented in Table 1 and Figure 6. She also completed a global rating of change (GROC) score at that time, rating herself as a 6 (a great deal better).

Table 2. *Kinematic and Kinetic Variables for Subject Number 1.*		
Kinematic & Kinetic Measurements		
	Pre-intervention	**Post-intervention**
Step Length	1.21 m	1.02 m
Step Rate	2.66 steps/s	3.37 steps/s
Vertical GRF	2316.99 N (2.42 BW)	2129.54 N (2.21 BW)
Impulse	382.10 Ns	314.19 Ns
m= meters; s= seconds; GRF= ground reaction forces; N= newtons; BW= body weight; Ns= newton seconds		

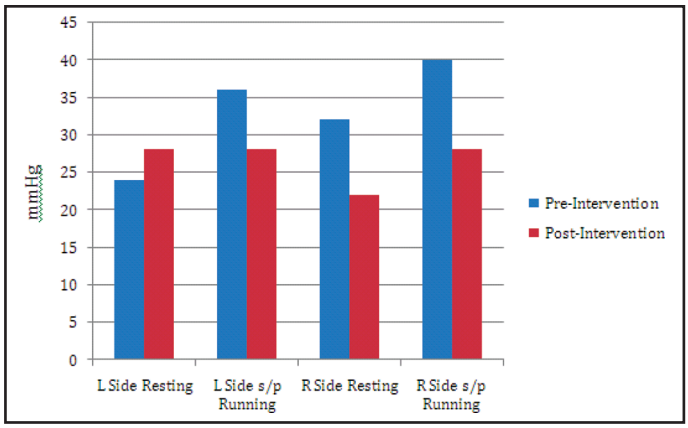

Figure 6. *Intracompartmental pressures of the anterior compartment for subject 1. Pre-intervention running pressures were measured after running 0.8 km while post-intervention running pressures were measured after running 5 km.*

A follow-up questionnaire was completed at 7 months, at which time the subject reported the ability to run 12.87 km (including) hills without an increase of leg symptoms and she reported that she was training to run a marathon.

CASE DESCRIPTION

Case 2: A 21-year old male (172.7 cm, 97.4 kg) presented to physical therapy with complaints of bilateral anterior and lateral lower leg pain while running seven months status post two-compartment (anterior and lateral) right leg fasciotomies (to correct CECS). He stated that his pre-surgical symptoms returned on the right leg within two months following surgery and now has a new onset of pain and tightness in the left leg. The patient reported that his left leg was now worse than the right, and his overall pain caused him to stop running after approximately 5 minutes. He verbalized concern that he may need a surgery on the left leg. He reported complete reduction of symptoms within 5 minutes of rest.

Similar to the first case, the physical examination was unremarkable at rest. However, this patient had noticeably hypertrophied lower legs (calf musculature). A running evaluation, utilizing visual analysis, was conducted on a commercial treadmill at a self-selected speed of 10.5 km/hr, during which he demonstrated a heel striking gait pattern. After running for 2 minutes, 30 seconds, he reported pain and tightness in the right anterior and lateral lower leg. After 0.81 km (5 minutes, 14 seconds), the subject noted the onset of pain and tightness on the left side. After 1.56 km (9 minutes, 11 seconds), a foot slap was observed on the left side at which time he requested to stop the activity. Physical exam immediately following revealed an appreciable firmness and tenderness to palpation in both anterior compartments. He complained of pain in the legs with resisted dorsiflexion (5/5 strength) and with full passive plantar flexion. Kinematic and kinetic data was gathered along with pre- and post-exercise intracompartmental pressures of the anterior compartments (Table 2 and Figure 7). The patient was diagnosed with CECS by an orthopedic surgeon and the intervention of modifying his running technique was initiated.

The running instruction and training mirrored that provided during case one, emphasizing a forefoot running pattern, increasing the step rate to 3 steps per second, and use of the hamstrings to pull his foot from the ground while running.[7]

OUTCOMES

After 6 weeks, the physical examination, intracompartmental pressures, and instrumented treadmill measurements were repeated. The physical examination was unremarkable before and after running. The patient ran 4.02 km (21 minutes, 8 seconds) on the treadmill without complaints of leg pain; however,

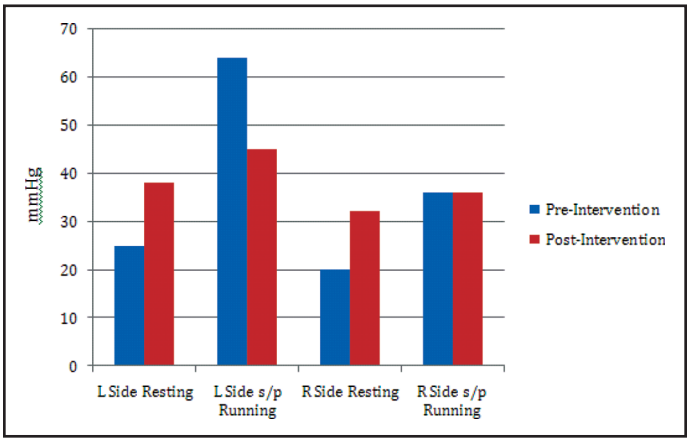

Figure 7. *Intracompartmental pressures of the anterior compartment for subject 2. Pre-intervention running pressures were measured after running 1.56 km while post-intervention running pressures were measured after running 4.02 km.*

the test was discontinued due to complaints of left foot arch pain. A subsequent physical exam of his foot and ankle was unremarkable. The kinematic and kinetic measurements and the pre- and post-intracompartmental pressures of the anterior compartments are provided in Table 2 and Figure 7. He also completed a GROC score at that time and rated himself as a 7 (a great deal better). After 2.5 months he reported he was able to run 6.43 km without pain. On a follow-up questionnaire at 7 months he reported running distances of 6.43 km pain-free 3 times a week.

DISCUSSION

This case series presents two subjects with CECS whereby altering running mechanics to a forefoot striking technique was the primary intervention. The subjects had favorable results which allowed them to return to pain-free running activity without surgical intervention. The change in running technique was demonstrated by increased step rate and decreased impulse, GRF, and step length (Tables 1 and 2). Post-exercise compartment pressures were lower by as much as 30% in some cases (Figures 6 & 7). In addition, these two subjects, who could not run over 1 km without severe symptoms prior to the intervention, could now run 4 and 5 km with minimal difficulty.

Successful rehabilitation for CECS has historically been challenging. Physical therapists typically perform patient examinations looking for impairments that can be addressed through therapeutic exercise, various modalities, or manual therapies. CECS is a unique condition whereby it is commonly very difficult to find impairments related to a patient's symptoms. Although research is certainly limited, this is potentially one reason why attempts at non-surgical management with anti-inflammatory drugs, stretching, prolonged rest, decreasing or avoiding the problematic activity, orthotics, and massage have largely proved unsuccessful. In these two cases, the selected intervention was not based on any specific impairment observed or measured during the physical examination. Rather, it was based on observing a heel striking gait pattern with running and the theory that decreasing anterior compartment muscle activity could potentially be beneficial for this condition.

There are several possible reasons to explain how the forefoot running training technique may assist those with CECS. Gershuni et al and Tsintzas et al found a significant increase in the anterior compartment pressures of healthy individuals in the full ankle dorsiflexion and full knee extension positions.[47,48] The position of full knee extension coupled with full ankle dorsiflexion is consistent with the typical heel strike technique used by runners at initial contact. In addition to a potentially more favorable foot position at initial ground contact (less ankle dorsiflexion), eliminating the heel strike upon ground contact by replacing it with a forefoot strike may reduce the eccentric muscle activity of the anterior leg compartment musculature and therefore mitigate the increase of anterior compartment pressures and symptoms of CECS during running.[21,47,48] As previously noted, Kirby et al reported that anterior compartment pressures were increased when a heel striking gait pattern was utilized as opposed to a neutral or forefoot running gait.[15] Therefore, a forefoot running technique may favorably reduce the variables that contribute to the onset of CECS symptoms and reduce the necessity for surgical management for this condition.

The cases presented in this paper are interesting for several reasons. In case one, the patient quickly adapted the new forefoot running technique. Compared to pre-intervention measures her impulse, ground reaction forces, and step length decreased by approximately 5%, 7%, and 9% respectively. Step rate

increased by approximately 9%. It is possible that altering these aspects of running mechanics favorably affected her during her rehabilitation as she was able to return to running without pain or limitation in 6 weeks.

Case two differs from case one in that he previously had a fasciotomy on his right leg, in which his CECS symptoms returned approximately 2 months after surgery when he resumed running. As his running distance progressed, his left leg became more symptomatic than the right, and his bilateral leg symptoms were consistent with CECS. Adjusting running technique and learning to pull the foot from the ground was challenging for this subject. No specific functional deficits were identified as contributors to this challenge. However, it is the authors' experience that some individuals have a more difficult time than others while attempting to perform a forefoot running technique. A great deal of attention to detail and video feedback was necessary for this patient. Ultimately, he avoided fasciotomy on his left leg and a revision fasciotomy on his right leg, and his running distance has continued to increase.

Ultimately, no cause and effect relationship can be inferred by the results of case report research. Interpretation of the current findings presents challenges related to the fact that pressure measurements post-intervention performed at rest and 1 minute following running could be considered elevated according to previous researchers.[18] For example, over 20 years ago, Pedowitz et al published that resting values higher than 15 mmHg and post exercise values over 30 mmHg were indicative of CECS with the caveat that elevated pressures without symptoms of CECS would not be considered a positive test.[49] Resting pressure values in these 2 subjects ranged from 20 mmHg to 32 mmHg while post running pressures ranged from 36 mmHg to 63 mmHg. Direct comparison to previously reported values should be cautioned, as conflicting values have been reported by several studies, with reports of normal intracompartmental pressures varying by up to 500%.[50,51] It has also been documented that pressure varies with the depth of the catheter placement, which is difficult to control.[52] These variables could explain the fact that resting pressures at 6 weeks were elevated compared to the resting pressures at baseline. We are unable to make direct comparisons of our pressure data to findings reported by Pedowitz et al due to the fact that their study used a slit catheter to establish CECS pressure criteria, and the current report describes pressures obtained via a side-port needle catheter. Despite elevated pressure readings, the subjects were asymptomatic. Therefor, they no longer met the diagnostic criteria for CECS; elevated pressures in the presence of other clinical findings.

Caution and careful instruction may be required to avoid undesired complications when one attempts to alter his or her current running style. Common complications include achilles tendonopathy, plantar fascia pain, gastrocnemius soreness, blisters, iliotibial band syndrome, and anterior knee pain.[45] Running errors while attempting to transition to a forefoot running gait pattern typically contribute to these musculoskeletal complaints and can be greatly reduced by careful supervision and correction during training. Similar to most new exercise programs, proper form and gradual progression in time and intensity must be emphasized. Additionally, patients presenting with leg pain should be evaluated by a credentialed medical provider.

While no generalizations or intervention recommendations can be made from this case series, it does illuminate the need for further research in this area. For those patients with CECS, adopting a forefoot running style may lead to an increased tolerance for running and therefore potentially decrease the need for surgical management of this condition. The authors are currently conducting a clinical trial with a larger sample size to further explore the effectiveness of forefoot running on those diagnosed with CECS.

REFERENCES

1. Shanthikumar S, Low Z, Falvey E, et al. The effect of gait velocity on calcaneal balance at heel strike; Implications for orthotic prescription in injury prevention. Gait Posture 2009;31:9-12.
2. Pollock ML, Gettman LR, Milesis CA, et al. Effects of frequency and duration of training on attrition and incidence of injury. Med Sci Sports 1977;9:31-6.
3. Barnes M. Diagnosis and management of the chronic compartment syndromes: a review of the literature. Br J Sports Med 1997;31:21-7.
4. Edmundsson D, Toolanen G, Sojka P. Chronic compartment syndrome also affects nonathletic

subjects: a prospective study of 63 cases with exercise-induced lower leg pain. Acta Orthop 2007;78:136-42.

5. Dreyer D, Dreyer K. ChiRunning: a revolutionary approach to effortless, injury-free running New York, NY: Fireside; 2009.
6. Robillard J. The barefoot running book Allendale, Michigan: Barefoot running press; 2010.
7. Romanov N. Pose Method of Running Coral Gables, FL: Pose Tech Press; 2002.
8. Squadrone R, Gallozzi C. Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. J Sports Med Phys Fitness 2009;49:6-13.
9. Romanov N, Fletcher G. Runners do not push off the ground but fall forwards via a gravitational torque. Sports Biomech 2007;6:434-52.
10. Lieberman DE, Venkadesan M, Werbel WA, et al. Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature 2010;463:531-5.
11. Fraipont MJ, Adamson GJ. Chronic exertional compartment syndrome. J Am Acad Orthop Surg 2003;11:268-76.
12. Edmundsson D, Toolanen G, Thornell LE, et al. Evidence for low muscle capillary supply as a pathogenic factor in chronic compartment syndrome. Scand J Med Sci Sports 2009:1-8.
13. Fehlandt A, Jr., Micheli L. Acute exertional anterior compartment syndrome in an adolescent female. Med Sci Sports Exerc 1995;27:3-7.
14. Shah SN, Miller BS, Kuhn JE. Chronic exertional compartment syndrome. Am J Orthop 2004;33:335-41.
15. Kirby RL, McDermott P. Anterior tibial compartment pressures during running with rearfoot and forefoot landing styles. Arch Phys Med Rehabil 1983;64:296-9.
16. Howard JL, Mohtadi NG, Wiley JP. Evaluation of outcomes in patients following surgical treatment of chronic exertional compartment syndrome in the leg. Clin J Sport Med 2000;10:176-84.
17. Mubarak SJ HA. Definition and terminology. In: Mubarak SJ HA, editor. Compartment Syndromes and Volkmann's Contractures. Philadelphia: W.B. Saunders; 1981. p. 1-4.
18. Pedowitz RA HA, Mubarak SJ, Gershuni DH. Modified Criteria for the Objective Diagnosis of Chronic Compartment Syndrome of the Leg. Am J Sports Med 1990;18:3540.
19. Detmer D, Sharpe K, Sufit R, et al. Chronic compartment syndrome: diagnosis, management, and outcomes. Am J Sports Med 1985;13:162-70.
20. Tzortziou V, Maffulli N, Padhiar N. Diagnosis and management of chronic exertional compartment syndrome (CECS) in the United Kingdom. Clin J Sport Med 2006;16:209-13.
21. Tweed JL, Barnes MR. Is eccentric muscle contraction a significant factor in the development of chronic anterior compartment syndrome? A review of the literature. Foot 2008;18:165-70.
22. Baker JF, Lui DF, Kiely PD, et al. Foot drop--an unusual presentation of exertional compartment syndrome. Clin J Sport Med 2009;19:236-7.
23. Farr D, Selesnick H. Chronic exertional compartment syndrome in a collegiate soccer player: a case report and literature review. Am J Orthop 2008;37:374-7.
24. Robinson MS, Parekh AA, Smith WR, et al. Bilateral exercise induced exertional compartment syndrome resulting in acute compartment loss: a case report. J Trauma 2008;65:225-7.
25. Schepsis AA, Gill SS, Foster TA. Fasciotomy for exertional anterior compartment syndrome: is lateral compartment release necessary? Am J Sports Med 1999;27:430-5.
26. Strauss MB. Chronic exertional compartment syndrome. Am J Orthop 2008;37:553.
27. Varelas FL, Wessel J, Clement DB, et al. Muscle function in chronic compartment syndrome of the leg J Orthop Sports Phys Ther 1993;18:586-9.
28. Anuar K GP. Systematic Review of the Management of Chronic Compartment Syndrome in the Lower Leg. Physiotherapy Singapore 2006;9:2-15.
29. Rorabeck CH, Bourne RB, Fowler PJ. The surgical treatment of exertional compartment syndrome in athletes. J Bone Joint Surg Am 1983;65:1245-51.
30. Schepsis AA, Martini D, Corbet M. Surgical management of exertional compartment syndrome of the lower leg. Am J Sports Med 1993;21:811-17.
31. Ardigo LP, Lafortuna C, Minetti A, et al. Metabolic and mechanical aspects of foot landing type, forefoot and rearfoot strike, in human running. Acta Physiol Scand 1995;155:17-22.
32. Bobbert MF, Yeadon MR, Nigg BM. Mechanical analysis of the landing phase in heel-toe running. J Biomech 1992;25:223-34.
33. Chi KJ, Schmitt D. Mechanical energy and effective foot mass during impact loading of walking and running. J Biomech 2005;38:1387-95.
34. De Wit B, De Clercq D, Aerts P. Biomechanical analysis of the stance phase during barefoot and shod running. J Biomech 2000;33:269-78.
35. Dickinson JA, Cook SD, Leinhardt TM. The measurement of shock waves following heel strike while running. J Biomech 1985;18:415-22.

36. Divert C, Baur H, Mornieux G, et al. Stiffness adaptations in shod running. J Appl Biomech 2005;21:311-21.
37. Divert C, Mornieux G, Baur H, et al. Mechanical comparison of barefoot and shod running. Int J Sports Med 2005;26:593-8.
38. Divert C, Mornieux G, Freychat P, et al. Barefoot-shod running differences: shoe or mass effect? Int J Sports Med 2008;29:512-8.
39. Edwards WB TD, Rudolphi TJ. Effects of stride length and running mileage on a probabilistic stress fracture model Med Sci Sports Exerc 2009;41:2177-84.
40. Heiderscheit BC, Chumanov ES, Michalski MP, et al. Effects of step rate manipulation on joint mechanics during running. Med Sci Sports Exerc 2011;43:296-302.
41. Morgan D, Martin P, Krahenbuhl G, et al. Variability in running economy and mechanics among trained male runners. Med Sci Sports Exerc 1991;223:378-83.
42. Nilsson J, Thorstensson A. Ground reaction forces at different speeds of human walking and running. Acta Physiol Scand 1989;136:217-27.
43. Boody AR, Wongworawat MD. Accuracy in the measurement of compartment pressures: a comparison of three commonly used devices. J Bone Joint Surg Am 2005;87:2415-22.
44. Allen MJ, Barnes MR. Exercise pain in the lower leg: chronic compartment syndrome and medial tibial syndrome. J Bone Joint Surg Br 1986;68:818-23.
45. Romanov N. Dr. Nicholas Romanov's Training Essays Coral Gables, FL: Pose Tech Press; 2006.
46. Romanov N. The Pose Method of Triathlon Techniques Coral Gables, FL: Pose Tech Press; 2008.
47. Gershuni DH, Yaru NC, Hargens AR, et al. Ankle and knee position as a factor modifying intracompartmental pressure in the human leg. J Bone Joint Surg Am 1984;66:1415-20.
48. Tsintzas D, Ghosh S, Maffulli N, et al. The effect of ankle position on intracompartmental pressures of the leg. Acta Orthop Traumatol Turc 2009;43:42-8.
49. Pedowitz RA, Hargens AR, Mubarak SJ, et al. Modified criteria for the objective diagnosis of chronic compartment syndrome of the leg. Am J Sports Med 1990;18:35-40.
50. Blackman P. A review of chronic exertional compartment syndrome in the lower leg. Med Sci Sports Exerc 2000;32:s4-s10.
51. Willy C, Sterk J, Volker HU, et al. The significance of intracompartmental pressure values for the diagnosis of chronic functional compartment syndrome: a meta-analysis of research studies of pressures in anterior tibialis during exercise stress. Unfallchirurg 1999;102:267-77.
52. Kirkeboe A, Wysneys A. Regional tissue fluid pressure in rat calf muscle during sustained contraction on stretch. Acta Physiol Scand 1982;114:551-6.